Evaluation and Intercomparison of Clouds, Precipitation, and Radiation Budgets in Recent Reanalyses Using Satellite-Surface Observations

**Accepted to Climate Dynamics*

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Motivation

- **Some progress has been made in predicting the interactions between clouds, precipitation, and the Earth radiation budget, yet still, some error and large intermodel spread still exists**
  - **Bony et al. 2004, Jiang et al. 2012, Stanfield et al. 2014, Dolinar et al. 2015**

- **Updated parameterizations successfully increase the skill of cloud and radiation predictions**
  - **Modelers need to know where to focus their efforts**

Goals of this study

- **Report on the remaining issues regarding the prediction of clouds, precipitation, and radiative fluxes in five reanalyses (20CR, CFSR, Era-Interim, JRA-25, and MERRA)**
- **Several NASA and DOE data products are used to evaluate the current reanalyzed fields**
  - **CERES MODIS/EBAF, TRMM, and ARM**

Tasks of this study

Task I: "Global" comparison (12-years of data 03/2000 – 02/2012)

- Current state of reanalyzed results (monthly means)
- Total cloud fraction (CF), precipitation rate (PR), and top-of-atmosphere (TOA) cloud radiative effects (CRE)

Task II: Define dynamic regimes and determine their biases

- Based on vertical motion at 500 hPa

Task III: Ground-based comparison at ARM sites

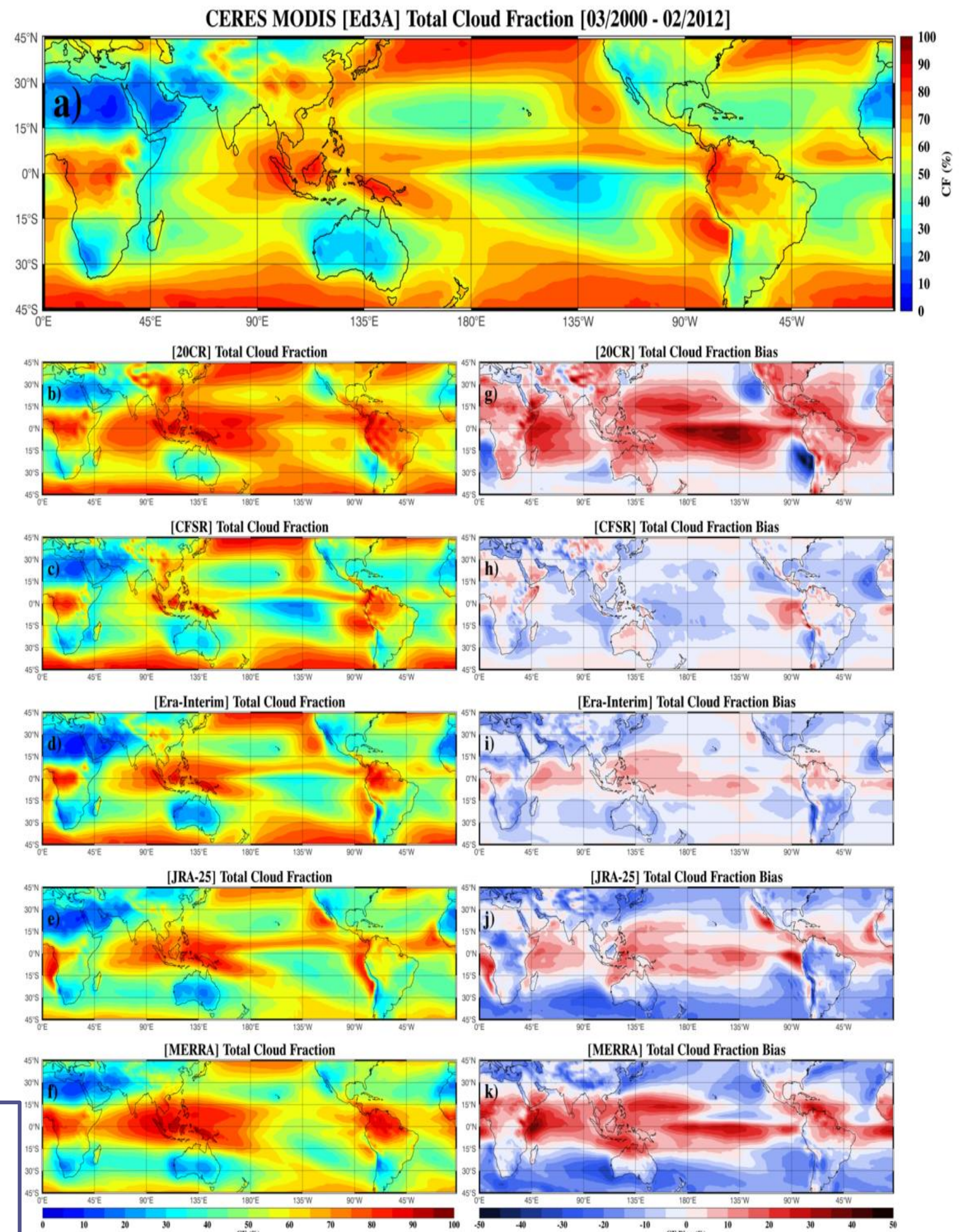
- Sites are within or adjacent to defined regimes, provides further validation

Global Comparison: Cloud Fraction (CF)

- **High CF in Southern Ocean, Northern Pacific and Atlantic, and the ITCZ**
- **Low CF in central Pacific and in arid climates (Sahara, Middle East, Australia, and SW North America**

- **Regional differences as high as 40%**
- **Overpredict CF over equatorial oceans (except CFSR) and some landmasses**
- **Underpredict MBL clouds, i.e. Southern Ocean, West Coastal North and South America**

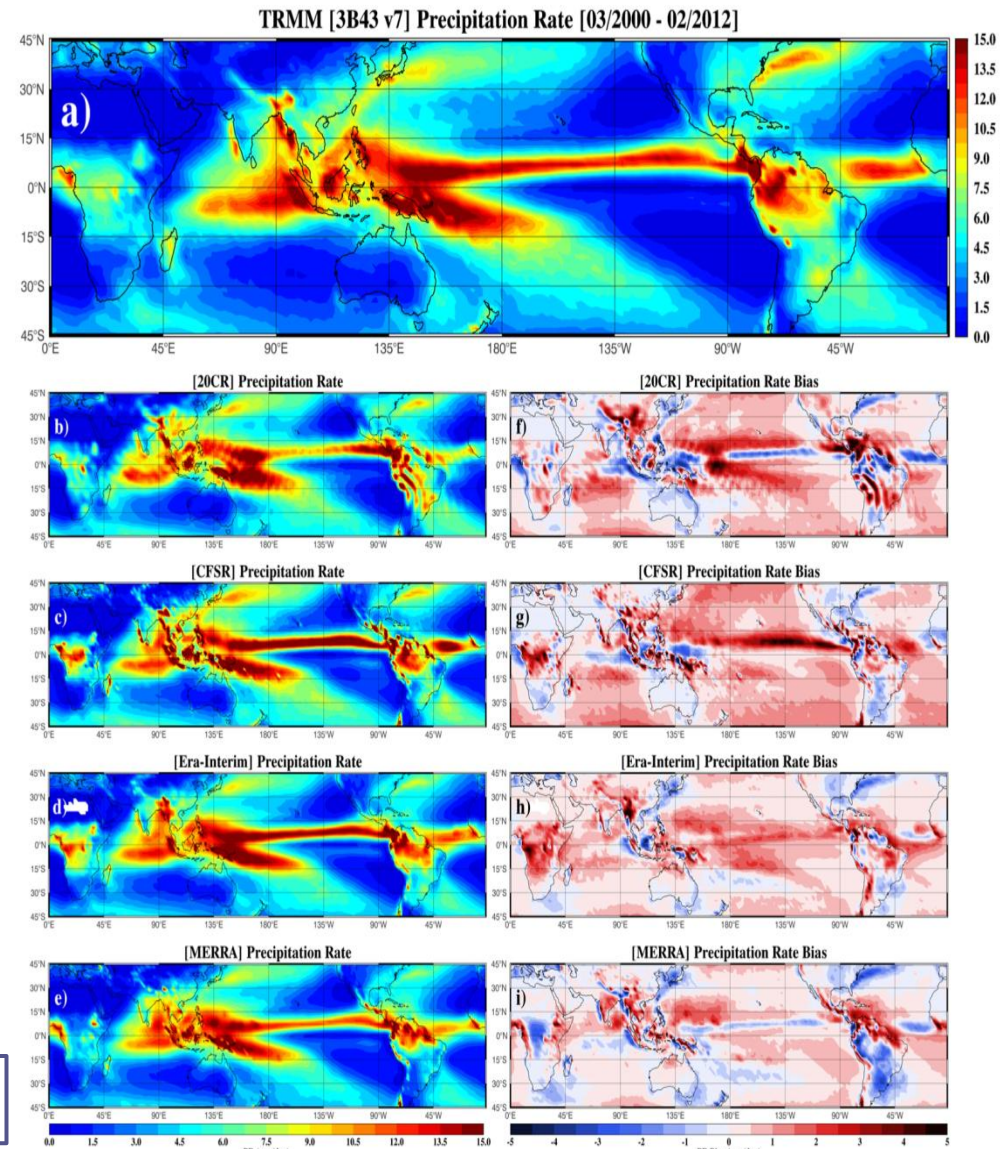
All reanalyses (except 20CR) underpredict CF!



Global Comparison: Precipitation Rate (PR)

- **High PRs associated with the ITCZ and mid-latitude storm tracks**

- **Areas of complex terrain (Andes Mountains and Tibetan Plateau) show difficulty in predicting PR**
  - **Issues with the diurnal cycle, orographic precipitation initiation, and/or mountain shadowing**
- **Issues with the ITCZ**
  - **Magnitude and placement of heaviest precipitation, i.e. Stanfield et al. 2015**

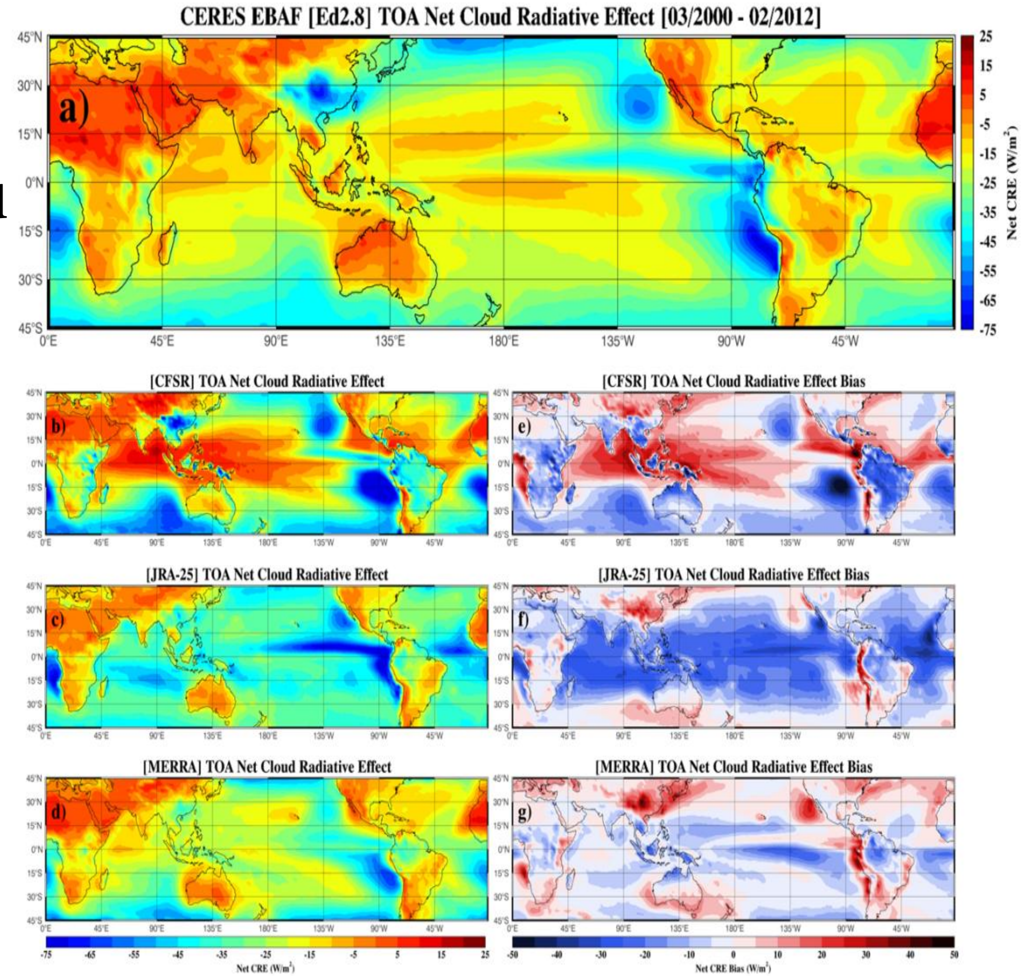


Reanalyses overpredict PR!

Global Comparison: Net Cloud Radiative Effect (CRE)

- **Strongest Net CRE (energy loss) over oceans (where MBL frequently occur) and over China**
- **Positive Net CREs occur in the arid climates due to the low frequency of clouds**

- ***CFSR:* Strongly underpredicted in the western tropical Pacific but overpredicted in the SE Pacific/Atlantic and Southern Ocean**
- ***JRA-25:* Strongly overpredicted in the tropics and extra-tropics, underpredicted in the mid-latitudes and over some land masses**
- ***MERRA:* Relatively small biases except some areas**



Reanalyses overpredict the Net CRE (more energy loss due to the presence of clouds)

Summary I

- **CF is underpredicted by all reanalyses (except 20CR)**

- **PR is overpredicted by the reanalyses**

	Observation	20CR	CFSR	Era-I	JRA-25	MERRA
CF (%)	56.7	64.1	53.4	53.9	52.1	55.0
PR (mm/day)	3.0	3.4	3.6	3.4	–––	3.1
$SWUP_{toa,all}$	96.6	93.2	94.7	–––	97.9	97.2
$SWUP_{toa,clr}$	48.5	–––	50.0	–––	48.6	49.1
OLR_{all}	253.8	250.4	258.4	260.0	269.7	257.0
OLR_{clr}	281.1	–––	281.3	279.1	288.5	283.6
SW CRE_{toa}	−48.1	–––	−44.7	–––	−49.3	−48.1
LW CRE_{toa}	27.3	–––	22.9	19.1	18.8	26.6
Net CRE_{toa}	−20.8	–––	−21.8	–––	−30.5	−21.5

- **Stronger (more energy lost) Net CRE (~1-10 W/m²) due to:**
  - **Weak (less energy gain) LW CRE**
    - **particularly due to the all-sky flux**
  - **Stronger SW CRE (JRA-25)**

Task II: Dynamic regimes: vertical motion at 500 hPa

- Strong ascent leading to deep convection in the tropics ($\omega 500 < -25$ hPa/day)
- Moderate to strong subsidence creates an environment favorable for low-level MBL stratocumulus clouds ($\omega 500 > 25$ hPa/day)

- Relatively constant LW CRE in the descent regime
- Strong increase in LW CRE with ω500 in the ascent regime

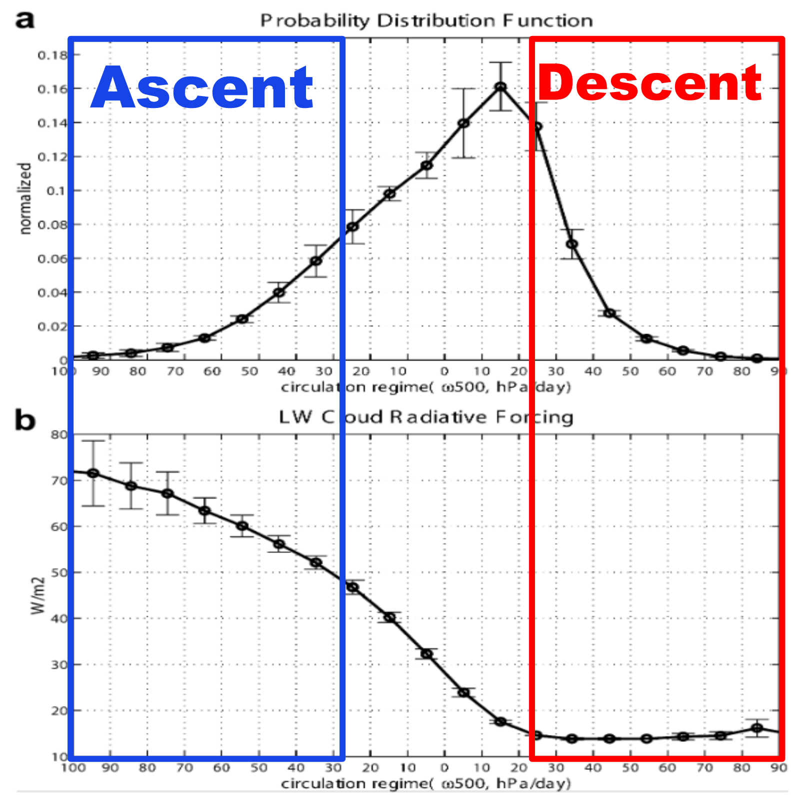
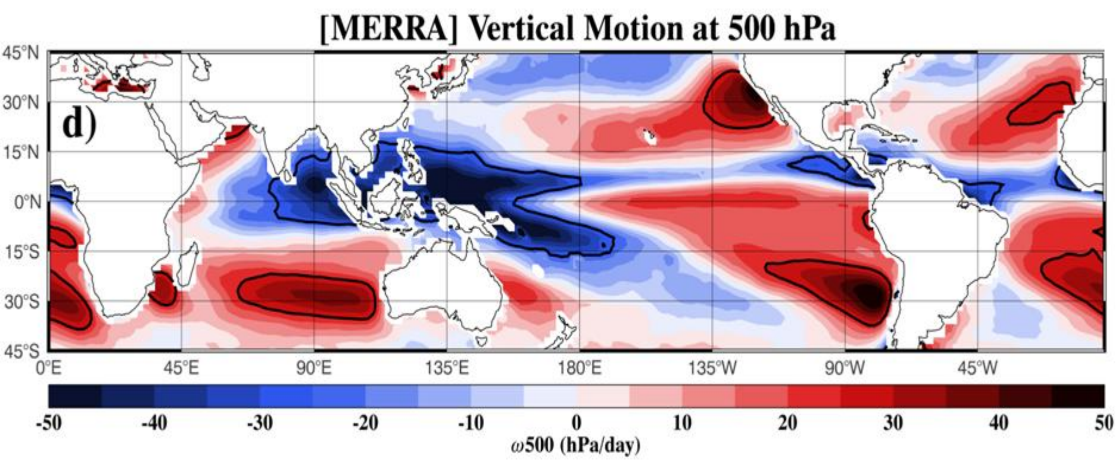


Fig. 2 from Bony et al. (2004)
ECMWF ω500 in the tropics (±30°) and ERBE CRE



How do the reanalysis predicted CF, PR, and TOA fluxes/CREs compare in the two regimes?

Regime Total Cloud Fraction (CF)

*No results from JRA-25 (ω500 unavailable)

Ascent (65.9%)

- **Overpredicted by all reanalyses**
  - **4.7 – 14.3% except CFSR (−7.7%)**
- **More convective-type clouds are predicted by the reanalyses**

Descent (59.8%)

- **Underpredicted by all reanalyses**
  - **−3.7 to −16.6%**
- **Fewer MBL stratiform clouds are predicted by the reanalyses**

Regime PR analysis

TRMM PDF in black

- Higher PRs in the ascent regime (8.37 vs. 1.03 mm/day)… suggests different cloud types
- On average, PRs are over predicted by 0.72 and 0.37 mm/day for the ascent and descent regime, respectively

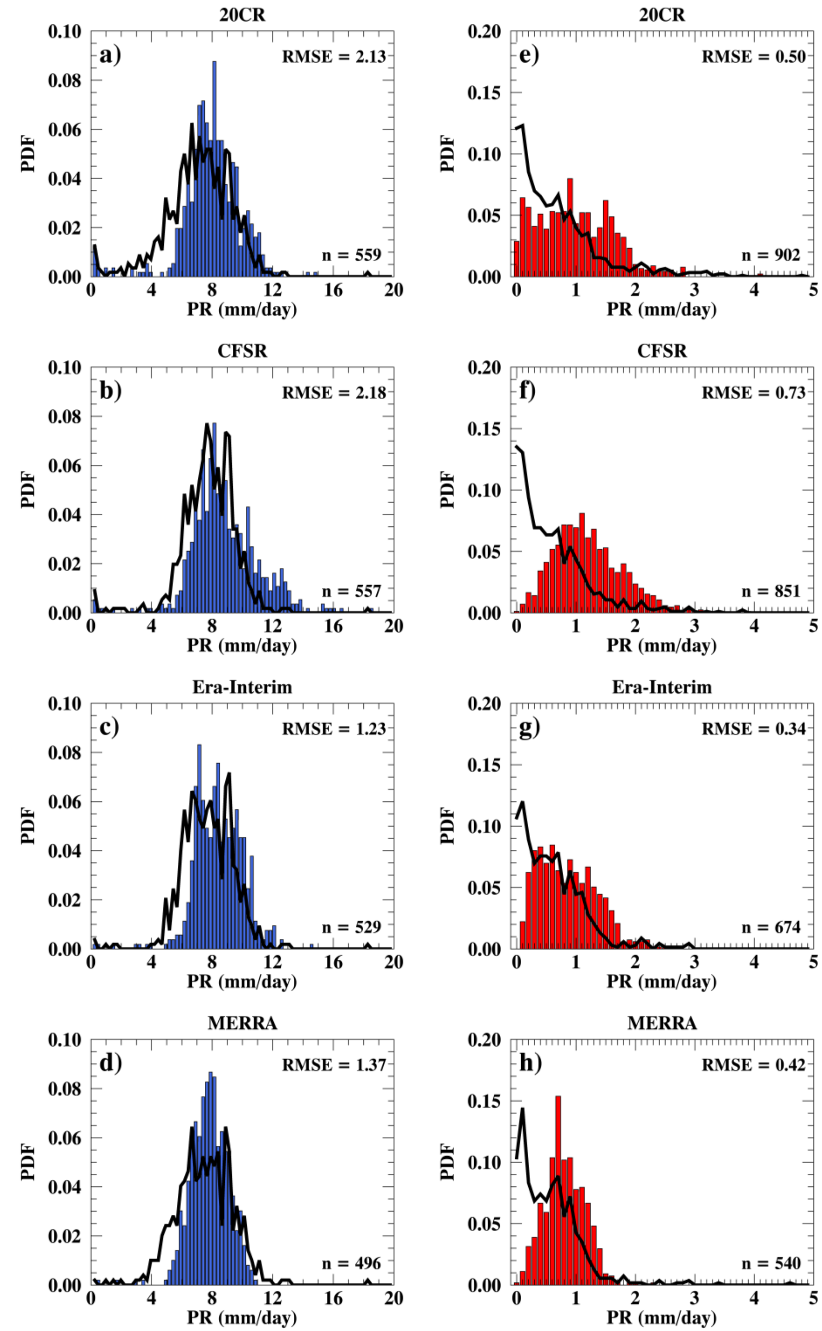
Observations

- Ascent regime PRs are normally distributed with a peak ~8 mm/day
- Descent regimes PRs are skewed to the left (lower PRs)

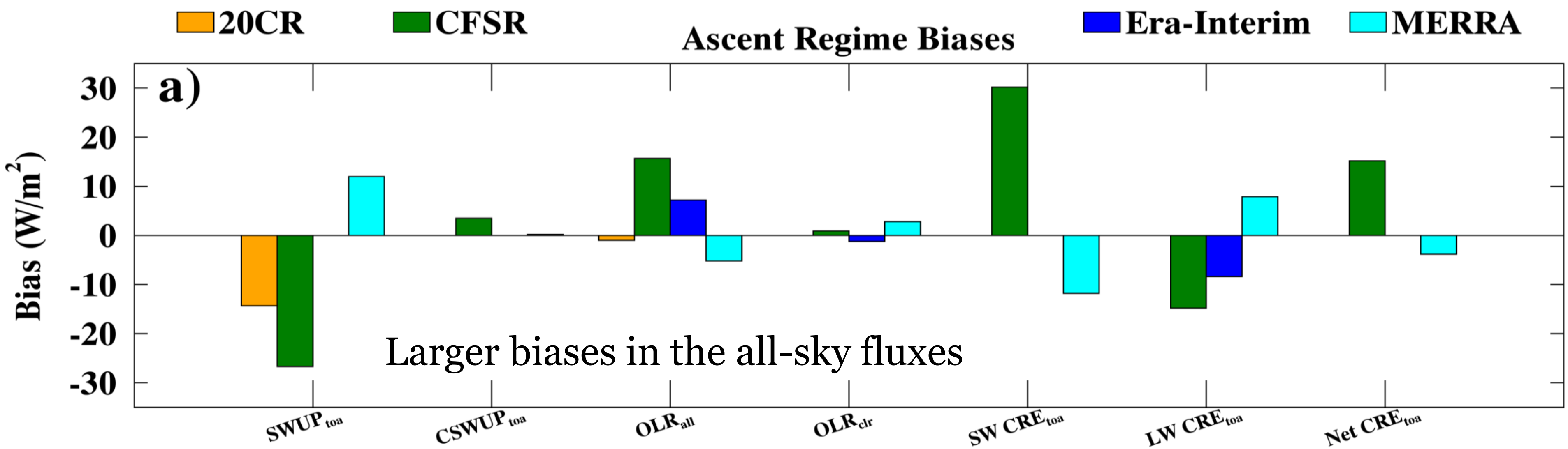
Reanalyses

- Ascent regime: PRs are normally distributed with a similar peak, but tend to underpredict PRs from 4-6 mm/day (CFSR overpredict PRs >~10 mm/day)
- Descent regime: different distributions; underpredict PR < 0.6 mm/day

Ascent Descent



Ascent Regime TOA fluxes and CREs

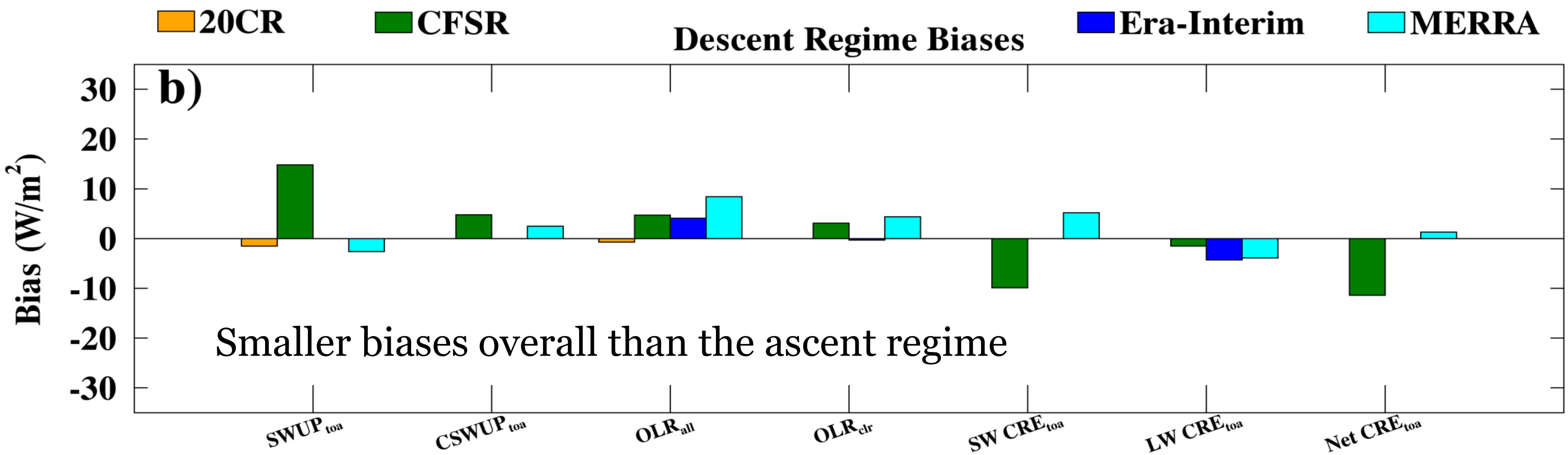


- **Large all-sky SWUP negative bias in CFSR contributes to the large bias in SW CRE (smaller energy loss)**
  - **Similar to the LW CRE (smaller energy gain)**

Radiative fluxes are consistent with CF results!

- **Positive bias in the all-sky SWUP in MERRA produces a stronger SW CRE (larger energy loss)**
  - **Similarly, less OLR relates to a stronger LW CRE (larger energy gain)**
  - **Net CRE negatively biased -> larger energy loss**

Descent Regime TOA fluxes and CREs



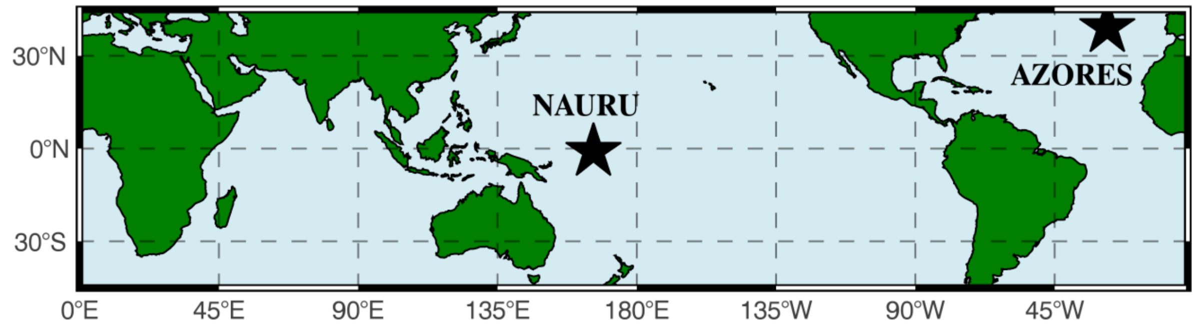
Calculated all-sky SWUP in CFSR is NOT consistent with CF (need info about cloud water path/optical depth)

Radiation fluxes are consistent with CF results in MERRA!

- OLR positively biased -> weaker LW CRE (less energy gained)
- Weaker Net CRE (SW CRE stronger than LW CRE)

Task III: Comparison at two ARM sites

Sites are within or adjacent to dynamic regimes



- **Azores (Graciosa Island, Eastern North Atlantic, ENA)**
  - 39° 5' 29.68" N, 28° 1' 32.34" W
  - 19 months of data from 06/2009 – 12/2010
  - Low-level marine BL stratocumulus clouds

- **Nauru Island (Tropical Western Pacific, TWP)**
  - 0° 31' 15.6" S, 166° 54' 57.60" E
  - 9 years of data from 03/2000 – 02/2009
  - Deep convective clouds

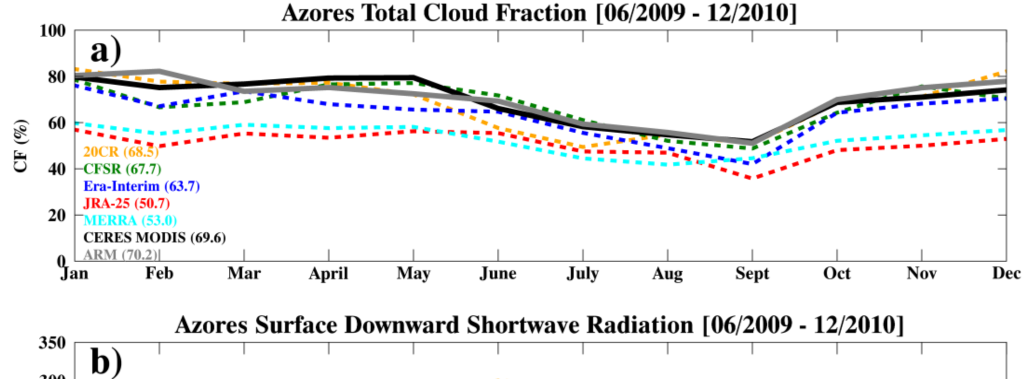
Azores (Graciosa Island, Eastern North Atlantic)

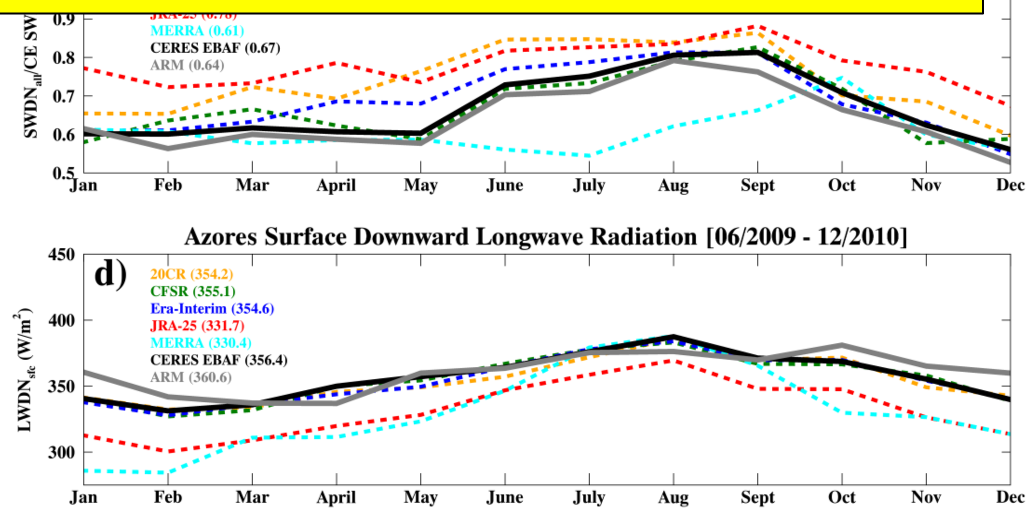
- **Observed CF ~70%**
  - Reanalyses underpredict
- **Observed SWDN ~162 W/m²**
  - Reanalyses overpredict
-

Although the reanalyses may be biased, their results are physically consistent:

lower CF →more surface SW transmission => less surface LWDN (related to cloud base temp/height)

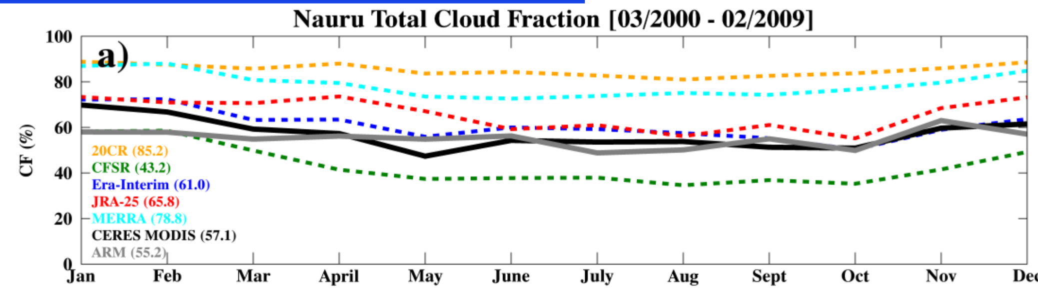
  - (except MERRA)
  - Reduce effects of latitude and the changes in SW flux
- **Observed LWDN ~358 W/m²**
  - Reanalyses underpredict



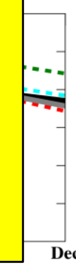


Nauru Island (Tropical Western Pacific)

- **Observed CF ~56%**
  - Reanalyses overpredict (except CFSR)



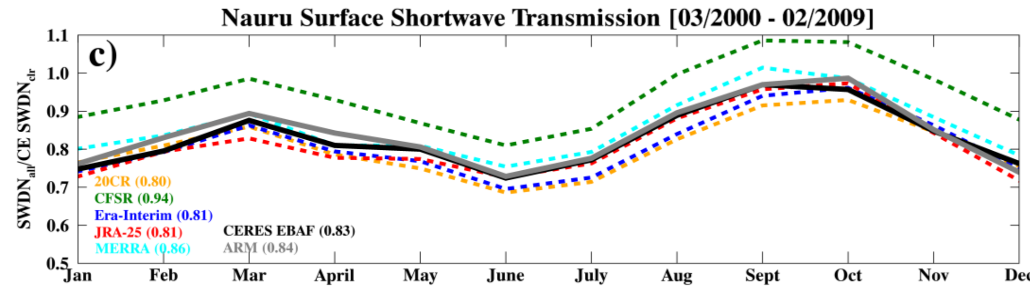
- **Observed SWDN ~247**



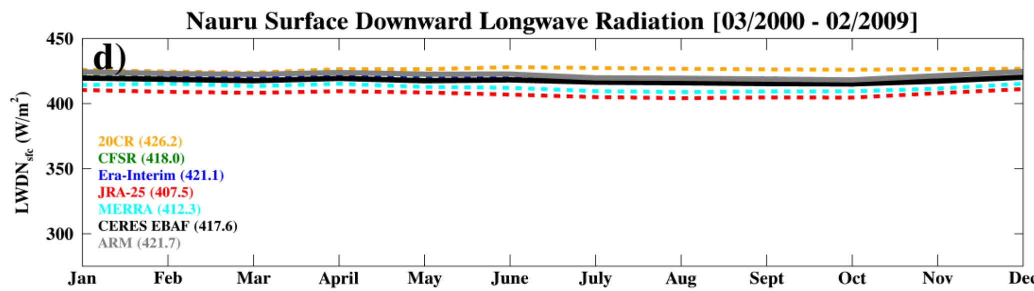
Although the reanalyses may be biased, their results are physically consistent:

higher CF → less surface SW transmission →more LWDN

- **Observed SW transmission ~0.84**
  - Reanalyses underpredict (except CFSR and MERRA)



- **Observed LWDN ~417-421 W/m²**
  - Reanalyses produce various results



Azores vs. Nauru

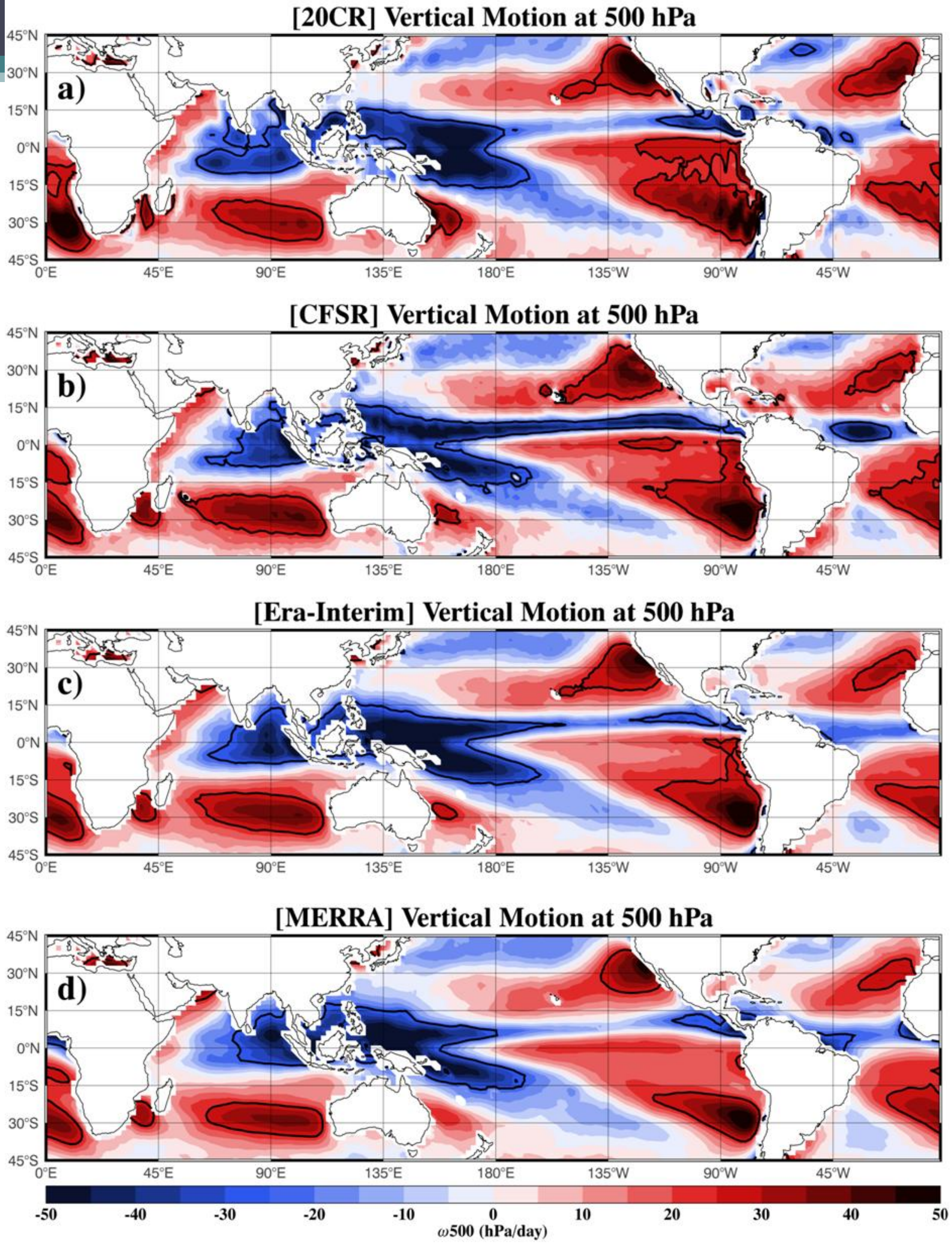
- **At Azores compared to Nauru:**
  - ~15% higher CF
  - ~20% less surface SW transmission
  - ~60 W/m^2 less LW radiation emitted to the surface

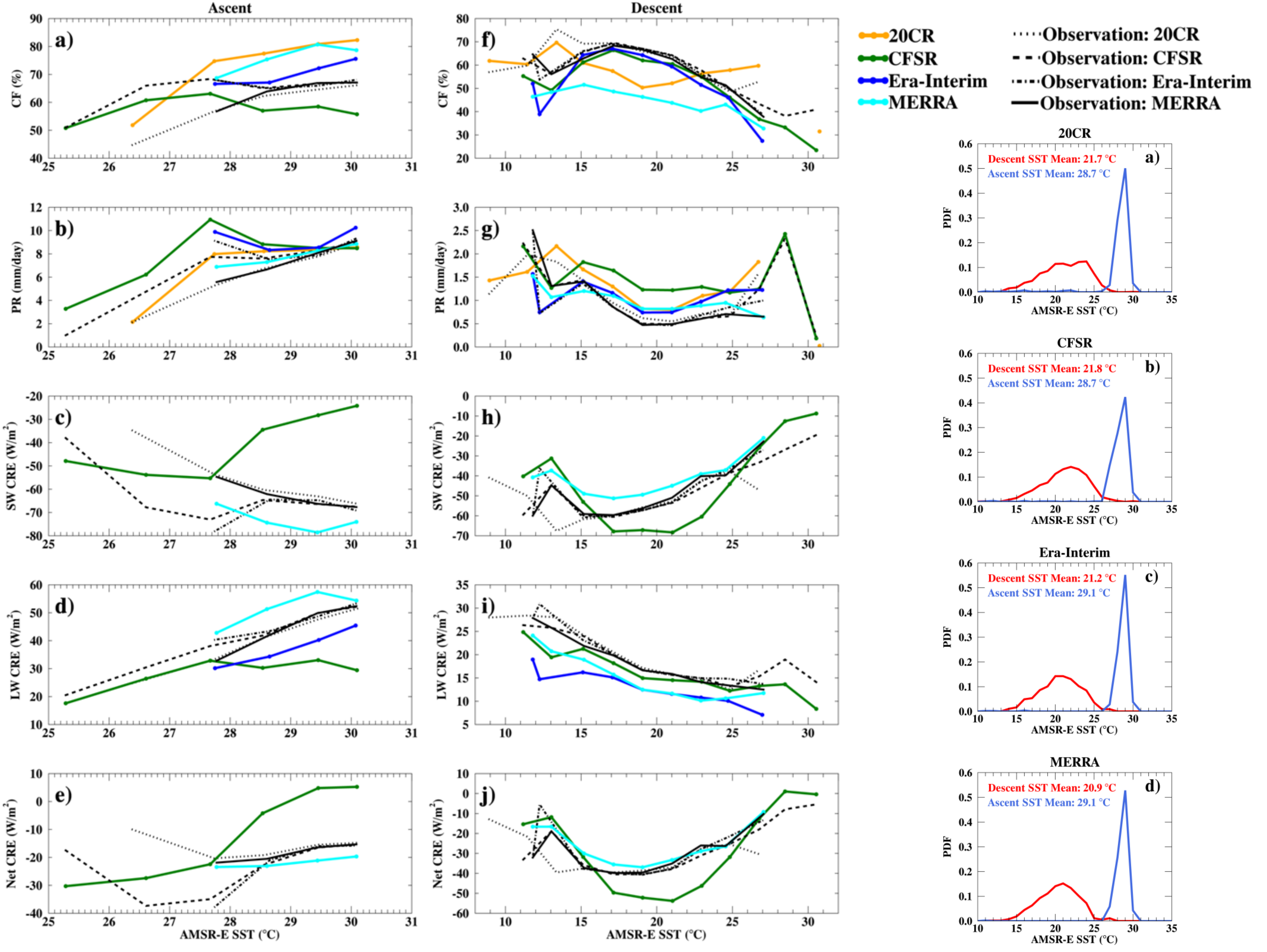
- **Less variation in CF and surface radiation fluxes at Nauru compared to Azores**
  - Presumably due to small seasonal and diurnal variations in cloud properties (e.g. cloud base temperature) and SST

The take away message…

- **Issues still remain in parameterizing convective and MBL clouds, as well as their impact on the radiation budget**
  - **Advancement in convective-type cloud parameterizations is slow due to their complexity/inhomogeneity (Wagner and Graf 2012)**
  - **Treatment of MBL stratus clouds in climate models is considered a large source of uncertainty in predicting any potential future climate change (Wielicki et al. 1995; Bony and Dufrense 2005)**
    - **Including aerosol effects on cloud microphysics and dynamics (Wood 2012)**

Supplemental


[20CR] Vertical Motion at 500 hPa
a)
[CFSR] Vertical Motion at 500 hPa
b)
[Era-Interim] Vertical Motion at 500 hPa
c)
[MERRA] Vertical Motion at 500 hPa
d)
45°N
30°N
15°N
0°N
15°S
30°S
45°S
0°E
45°E
90°E
135°E
180°E
135°W
90°W
45°W
-50
-40
-30
-20
-10
0
10
20
30
40
50
ω500 (hPa/day)


Ascent
Descent
20CR
CFSR
Era-Interim
MERRA
Observation: 20CR
Observation: CFSR
Observation: Era-Interim
Observation: MERRA
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
CF (%)
PR (mm/day)
SW CRE (W/m2)
LW CRE (W/m2)
Net CRE (W/m2)
AMSR-E SST (°C)
20CR
Descent SST Mean: 21.7 °C
Ascent SST Mean: 28.7 °C
CFSR
Descent SST Mean: 21.8 °C
Ascent SST Mean: 28.7 °C
Era-Interim
Descent SST Mean: 21.2 °C
Ascent SST Mean: 29.1 °C
MERRA
Descent SST Mean: 20.9 °C
Ascent SST Mean: 29.1 °C
PDF